On the possible discovery of ''exomoons'' in exoplanetary transits

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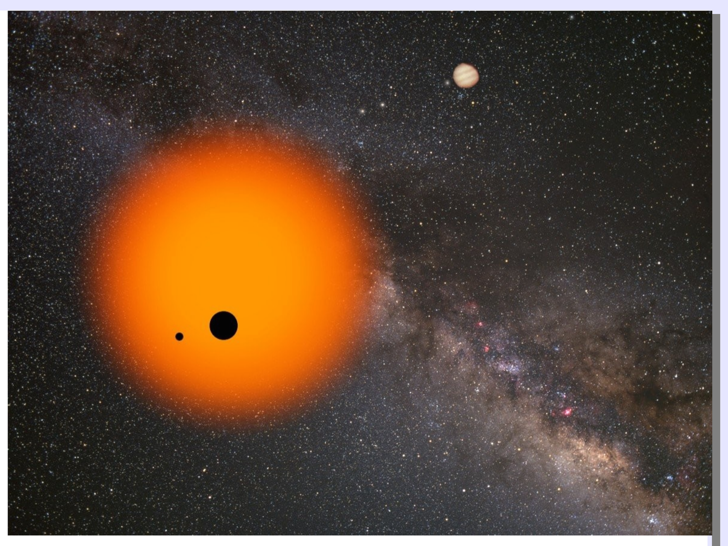
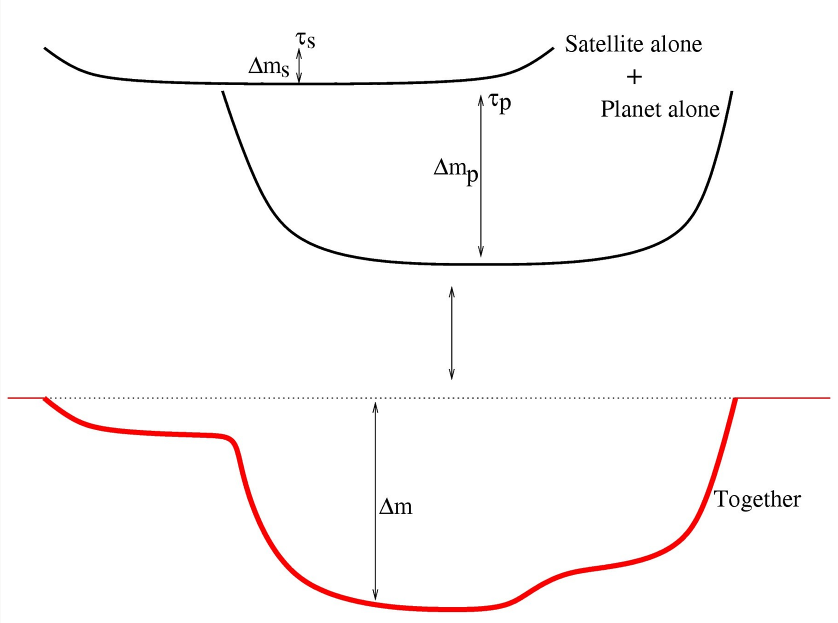
Discovery of a habitable planet is the great challenge of today's astronomy. This planet must have an appropriate climate (including favorable temperature, atmosphere, etc.), which has to reside over a long time to support the evolution of life. Our Habitable Planet has the Moon, whose role is extremely important in stabilizing the rotation axis, consequently the climate of the Earth. Similarly, *a satellite around a habitable exoplanet may sign an increased probability of extraterrestrial life.*



Here we propose a robust method which can be applied to current space-mission data and can lead to the discovery of satellites around Earth-like planets.

Detection Techniques



The lightcurve is composed by planet-alone and satellite-alone light curves.

A satellite causes small, certain distortions of the light curve. If we detect this photometric effect directly, this confirms the satellite. The ingress/egress timings may also vary, in which case a satellite is also likely to be present (Sartoretti & Schneider, 1999). *Our method offers an opportunity for the detection of satellites even if the noise is too high for a direct detection.* CoRoT (Auvergne et al., 2003) and Kepler (Borucki et al., 2003) space missions achieve ca. 0.01--0.1 mmag accuracy, which is slightly smaller than the magnitude of the distortions due to a satellite. Our method is a robust analysis of **all** the data points, and is therefore very suitable for their measurements.

The Application of the Method

The photometric central time of the transit, τ is

$$\tau = \frac{\sum t_i \Delta m_i}{\sum \Delta m_i}$$

where m_i is the i-th magnitude measurement at t_i time. If the sampling of the light curve is uniform, this τ exactly coincides with the transit of a unique point fixed on the planet-satellite line: the photocenter (Simon et al., 2007). In the absence of satellites, the light curve of a single planet is simple and the photocenter coincides with the barycenter: the transit timings occur strictly monoperiodically. If there is a satellite around the planet:

- the planet,
- the satellite, and therefore
- the photocenter

orbit the barycenter.

The farther the photocenter is from the barycenter, the more **photometric Transit Timing Variation (TTV_p)** occurs. The most likely detectable satellites have big size, low density and orbit far from the planet.

We calculated and numerically simulated light curves of many transiting systems. The aim was to test the required sampling rate and the photometric accuracy for the detection of satellites in various planet-satellite systems (Szabó et al., 2006).

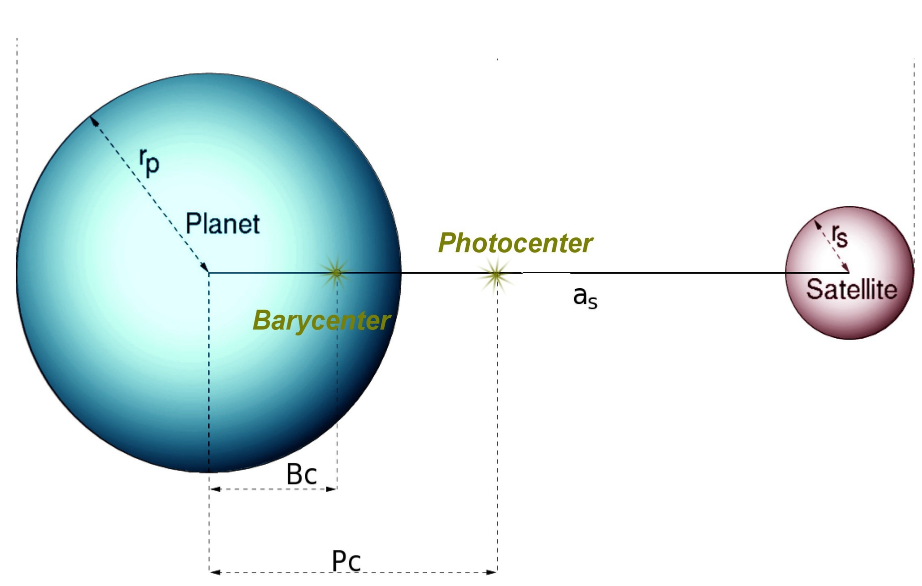
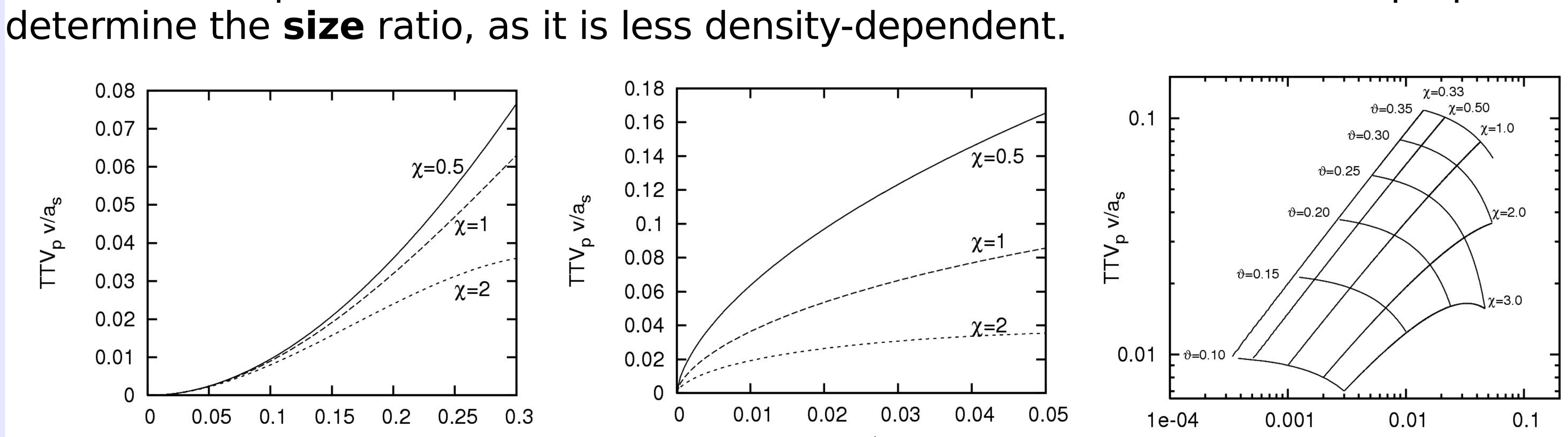


***Figure:* Position of the barycenter and the photocenter in a transiting system (not to scale).**

Size or mass determination?

The distance between the barycenter and the photocenter depend on the mass, diameter and density ratios (Simon et al., 2007). With a reliable density estimation the other two parameters can be calculated. Without this estimation, we propose to determine the **size** ratio, as it is less density-dependent.

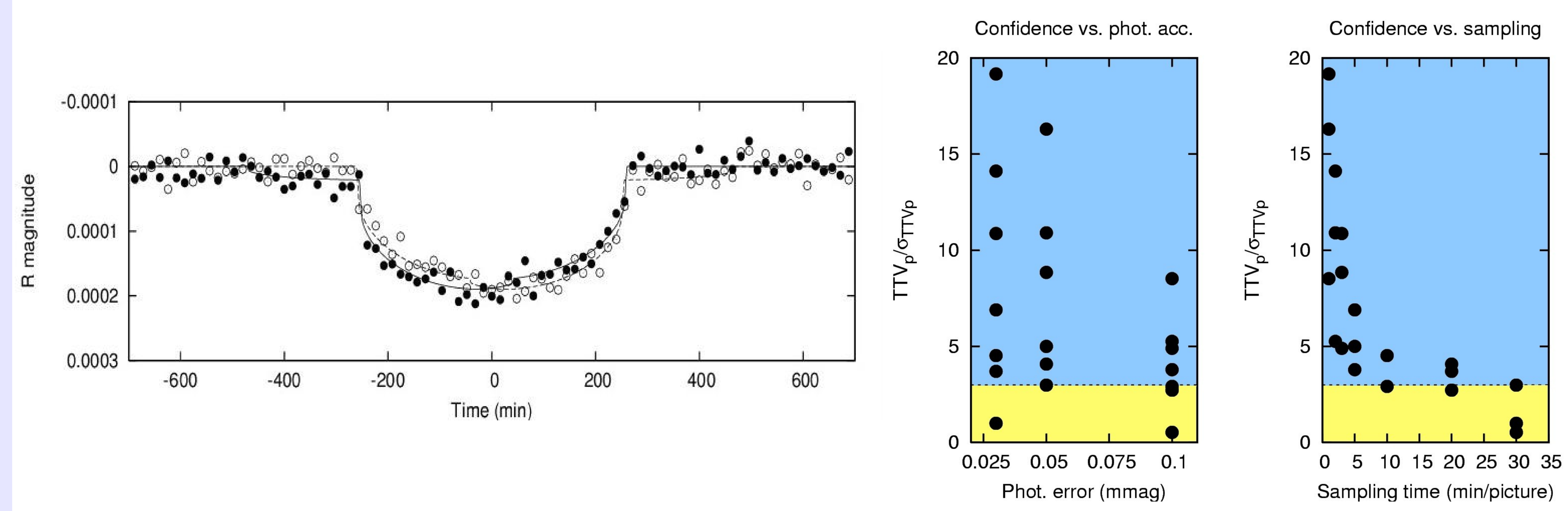


The dependence of the TTV_p on the ratio of the sizes (left panel) and the masses (middle panel). The three different curves show three satellites with different $\chi=\rho_{satellite}/\rho_{planet}$ density ratios. The method is less density-dependent for size determination. Right panel: a grid representation show the plausible satellite models for a given TTV_p.

Can We Discover an Earth-Moon-like System?

The photometric effect of our Moon is only 0.009 mmag, as one would observe it remotely. This is less than the presently attainable photometric accuracy, but with our method there is still hope for such a detection. We modeled systems with a solar analog star, an Earth-mass planet with 1 year orbital period, and a Moon-mass satellite with 29 days orbital period. We simulated Kepler-quality measurements, and found 5 detections in 20 calculations. We also determined the mass and the size of the companion, and got good results (within a factor of 2 to the real values). These results show that the detection is not too likely, but the possibility cannot be excluded.

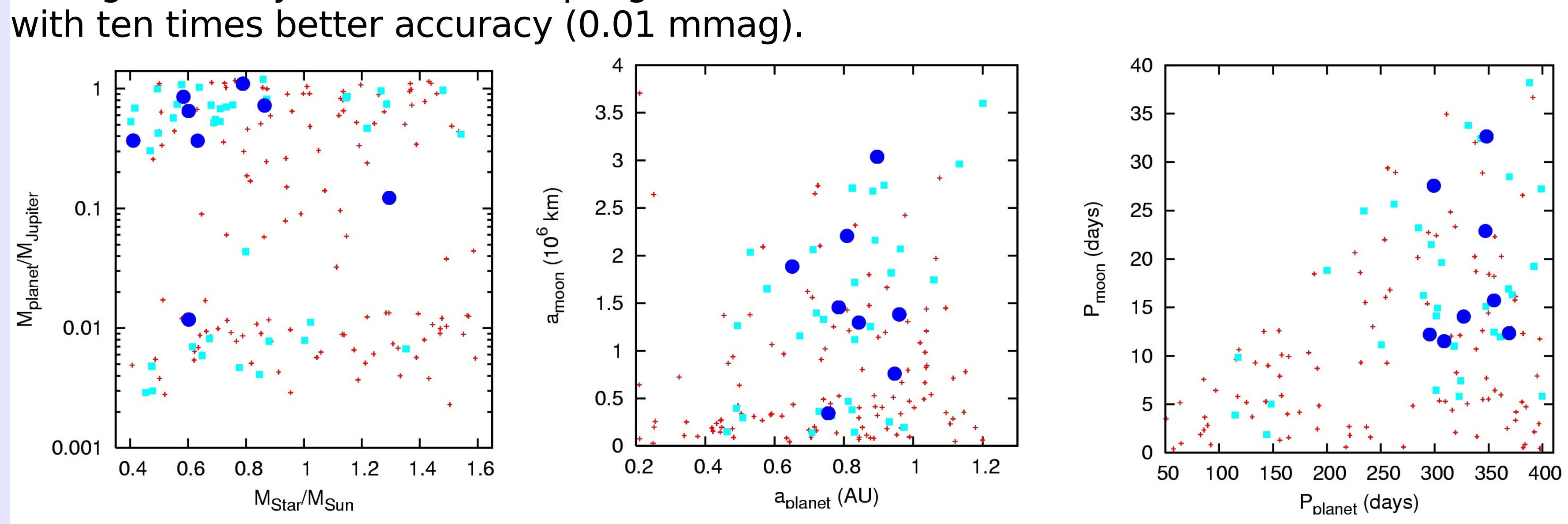
In a similar system, we studied the effect of sampling and photometric errors. We conclude that **the detection is primarily determined by the sampling rate.** Even with the worst photometric accuracy, we got better detection than 3-σ if the sampling rate was 1 or 2 minutes. On the contrary, no positive detection was found with 30-minute sampling rate, and the positive detections with 10 and 20-minute sampling rates are also rather ambiguous.



***Left:* Simulated observations of an Earth-sized planet and a Moon-sized moon before $0.7M_{Sun}$ star. The 5-minute average data points of expected Kepler-quality are shown; filled and open circles show observations with leading and trailing moon. The TTV_p is even detectable with 3-σ. *Right:* The detectability of TTV_p vs accuracy (as 0.1, 0.05, 0.025 mmag) and sampling rate (as 1, 2, 5, 10, 20, 30 minutes). TTV_p/σ_{TTVp} is the confidence level (i.e. how-many-sigma detectability), positive detection is expected in blue areas.**

Various Detectable Systems

To decide which exomoons can be really observed we designed a Monte-Carlo-like simulation. The simulated transit observations were randomly set up, and we checked if the TTV_p of the moon is observable with at least a 3-σ confidence. 500 systems were designed with giant and Earth-like planets, different inclinations and orbital periods, where the period of the planet did not exceed 400 days in order to have at least 4 transits during the planned operation time of Kepler. Two subset of model measurements were calculated. One reflected the quality of Kepler and CoRoT (0.1 mmag accuracy, 1-minute sampling rate), and a ''future observable'' set was calculated with ten times better accuracy (0.01 mmag).



Successfully detected satellites in 4-year long, simulated light curves. The photometric accuracy was 0.1 mmag (large dots) and 0.01 mmag (triangles). Small crosses represent the undetected systems.

We found 51 ''future observable'' systems and 8 ones which could be observed with the present accuracy. Both giant and Earth-like planets can have observable moons. The present equipments allow the detection of moons of giant planets around red dwarf stars, and one positive detection suggests that there is chance in case of Earth-like planets, too. All planets were at least 0.6 AU and 0.4 AU far from the star in case of present and future accuracy simulations. A moon orbiting farther from the planet is more likely to be detected. The planet has to have at least 280 days orbital period for promising detections. A few transits can be expected during a 4-year mission, and therefore the exploration of exomoons should be considered to be a long-time project.

Future Prospects

Based on the presented calculations, one may estimate the number of the expected detections with CoRoT, Kepler and the forthcoming missions. The total number of the Earth-sized planets to be discovered is a few hundred in the following decade. If only 5 percent of them have a moon similar to our Moon, and only every fifth moon will be really found, we even should get some detected and confirmed exomoon. In the favorable case, we may have a few known exomoons by the end of the next decade.

References

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